Assesment of potential swelling of Pressurized Water Reactor internals The GONDOLE experiment in Osiris reactor

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OUTLINE

1. The Gondole program
    1. Objectives
    2. Density specimens
    3. Irradiation conditions
    4. Density measurements experiments

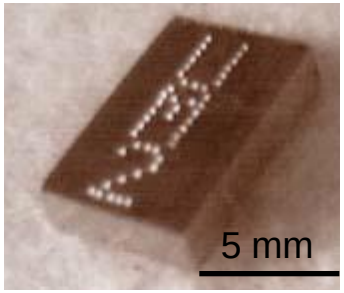
2. Results
    1. Density measurements
    2. TEM characterizations

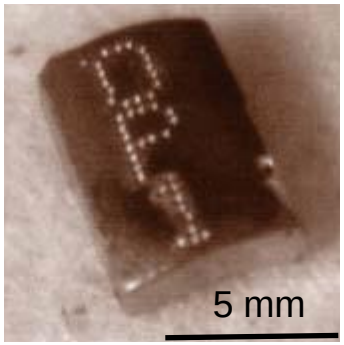
3. Conclusions and prospects

1.1. THE GONDOLE PROGRAM - OBJECTIVES

- Main goal: to evaluate potential swelling of PWR internals
- by density measurements
- PWR internals representative materials
- Irradiation in a mixed spectrum (Osiris MTR) at 360°C
- 30 cumulated dpa (15 dpa for initial program + 15 dpa for prolongation)

- Density specimens characteristics:
- Nominally rectangular shape
- Small size
- 7.7 × 5 × 1.5 mm^3
- Specimen reference engraved

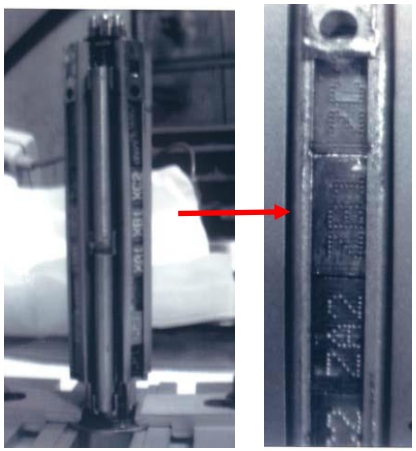




1.2. THE GONDOLE PROGRAM – DENSITY SPECIMENS

- Virgin and pre-irradiated materials (reach higher doses)
- 304 / 316 type materials (metallurgical state and chemical composition), with in particular “PWR reference materials” (304 Solution Annealed and 316 Cold-Worked + 308 welds) – French irradiation programs, PWR core internals materials, archive materials
- Others materials (stabilized steels, “low activation” steel…)

- Specimens inserted in four barrels in two baskets in SEMI/CEA hot cells
- 64 specimens



1.3. THE GONDOLE PROGRAM – IRRADIATION CONDITIONS

- Irradiation program: 2 parts
- 2005-2010: 5 phases (6 cycles each)
- 2011-2015: 3 phases (11, 10 and 9 cycles)
- ~ 1206 Equivalent Full Power Days

- Irradiation in the core of Osiris reactor
- Fast flux ~ 2×10^{14} n/cm²/s
- Thermal flux ~1.4×10^{14} n/cm²/s

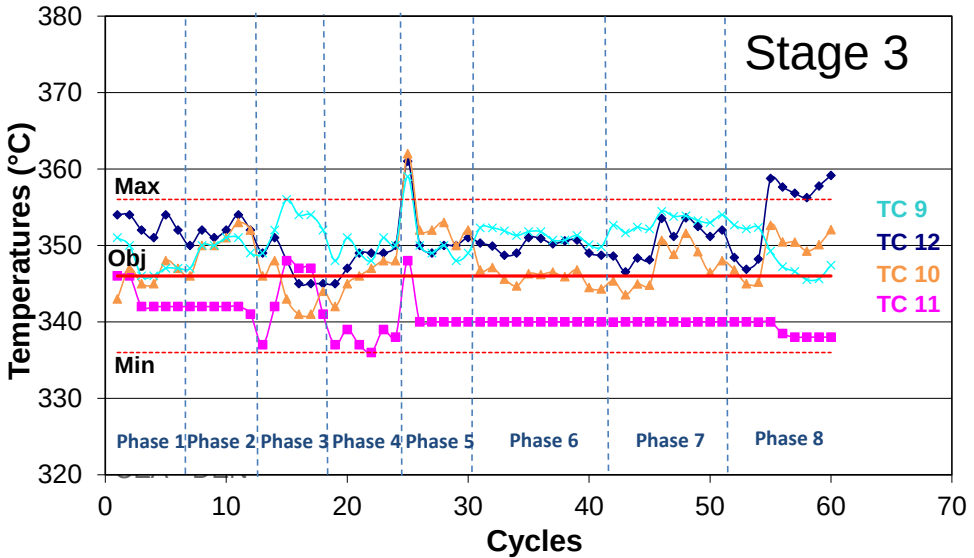
- Doses

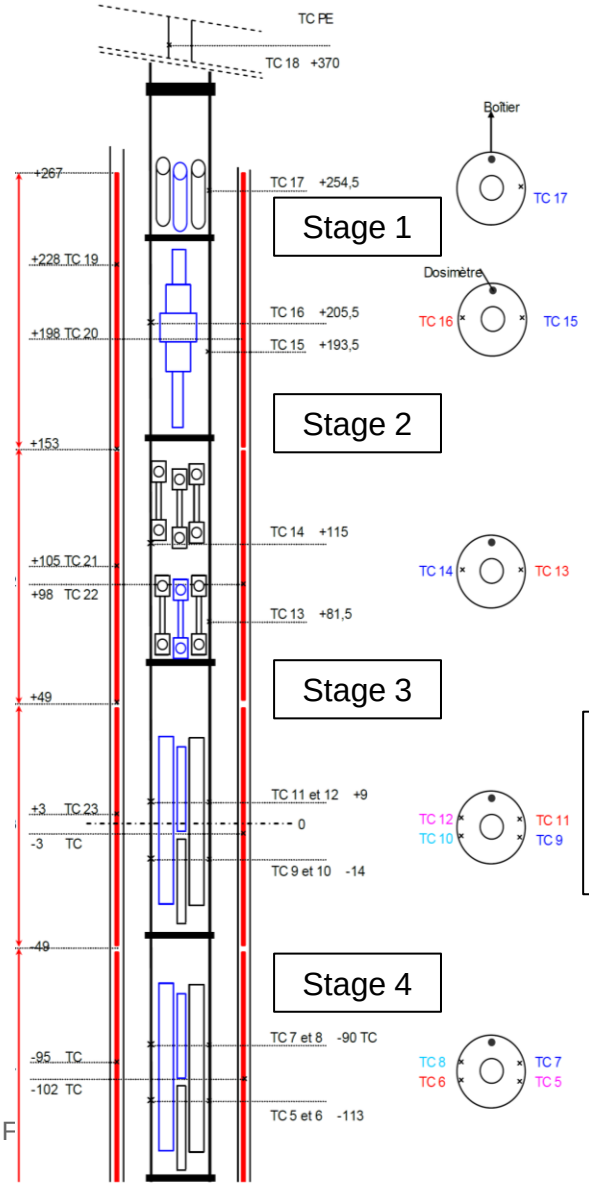
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8	Cumulated dose (dpa)
Dose (dpa Fe)	2.50	2.41	3.25	3.05	2.82	5.75	5.13	4.65	29.56

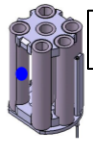
- Gradient along the sample holder: results at max flux plane
- Final cumulated dose ~29.6 dpa
- Specimen changes at phase 1 and 2: only a part of the specimens cumulated the whole dose, but from phase 3 specimens were not changed (except one) (~24.7 dpa at the max flux plane)

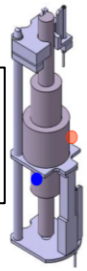
1.3. THE GONDOLE PROGRAM – IRRADIATION CONDITIONS

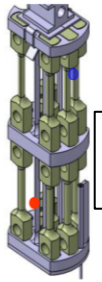
- Sample holder immersed in NaK
- 4 stages:
- Density specimens (stages 3 and 4)
- Other specimens (stages 1 to 4)
- Heaters and thermocouples for temperature regulation
- ~ 346°C on thermocouples for 360°C mean temperature on density specimens
- Activation foils for dosimetry measurements



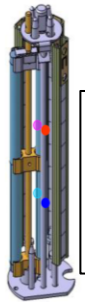



O-rings


Thermal gradient specimen


Tensile specimens


Density specimens TEM/SPT disks


Density specimens TEM/SPT disks

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Density measurement principle
- Immersion density method by double wheighing in air and phenyl bromide

Mass in air

$$\rho = \frac{(M1 - m1)}{(M1 - m1) - (M2 - m2)} \times \left(d_{PhenylBromide} - d_{air}\right) + d_{air}$$

Mass in liquid

- Immersion density measurements performed before GONDOLE irradiation and after each irradiation phase in hot cells
- Possibility to determine density evolution between phase 'j' and former phase 'i'

$$\Delta d(\%) = \frac{\rho_j - \rho_i}{\rho_i} \times 100$$

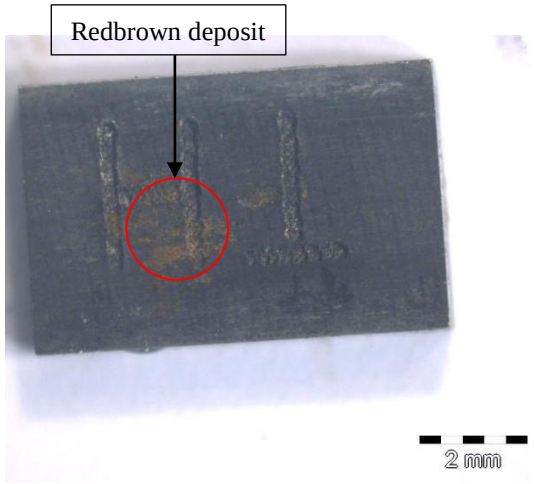
1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Choice of the density specimen geometry is a compromise:
- Size/mass of the specimens
- Common geometry for pre-irradiated material machining in hot cells
- Placing many specimens in the sample holder for material comparison

➢ Reduced weight of specimens (between 0.2 and 0.5 g) not optimal for density measurements (strong impact on uncertainty)

- Specimens were initially not checked
- Surface checked after phase 6

- Deposit confirmed on density specimens



➢ Enhancement of the density measurement protocol during the program

➢ Work to define the uncertainty as precisely as possible

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Density measurement procedure

➢ Phase 0 to phase 4:

Specimen cleaning in US bath (alcohol, 5 min)
2 double weighings (taking account of $T_{phenylbromide}$ and P_{air})
If the two densities differ of > 0.02 g/cm^3 the measure is repeated
Scales precision: 0.1 mg

➢ Phase 5:

Similar protocol to that of phase 4 but with **4 double weighings** and a new set of scales (**precision: 0.01 mg**) to improve accuracy

➢ Phase 6:

Specimen cleaning in US bath (alcohol, increased time 20 min), optical observation and weighing
Cleaning steps are repeated until mass stabilization
4 double weighings (30 specimens measured)

➢ Phase 7:

Similar protocol to that of phase 6
Daily calibration of the scales and increased cleaning efforts

➢ Phase 8:

Similar protocol to that of phase 7
5 double weighings

1.4. THE GONDOLE PROGRAM – DENSITY MEASUREMENT EXPERIMENTS

- Uncertainty determination

1 - Theoretical measurement uncertainty (precision of each measurement)

Accuracy limit on small samples (0.2 g)

Phase 1 - 4: +/- 0.40% (97.5% due to mass uncertainty)

Phase 5 - 7 : +/- 0.05% (80% due to mass uncertainty) – new scales

2 – Measurement scatter

Limited numbers of measurements : Student-Law approach

$$\mu = \pm t_{1-\frac{\alpha}{2}}^{n-1} \times \frac{\sigma}{\sqrt{n}}$$

n: number of measurements ($n_{phases\ 1\text{-}4}$=2, $n_{phases\ 5\text{-}7}$=4, $n_{phase\ 8}$=5)

α: risk of error, taken equal to 5 %

σ: standard deviation for the n measurements

$t_{1-\frac{\alpha}{2}}^{n-1}$: Student law quantile for n-1 level of freedoms and with an error risk of α/2

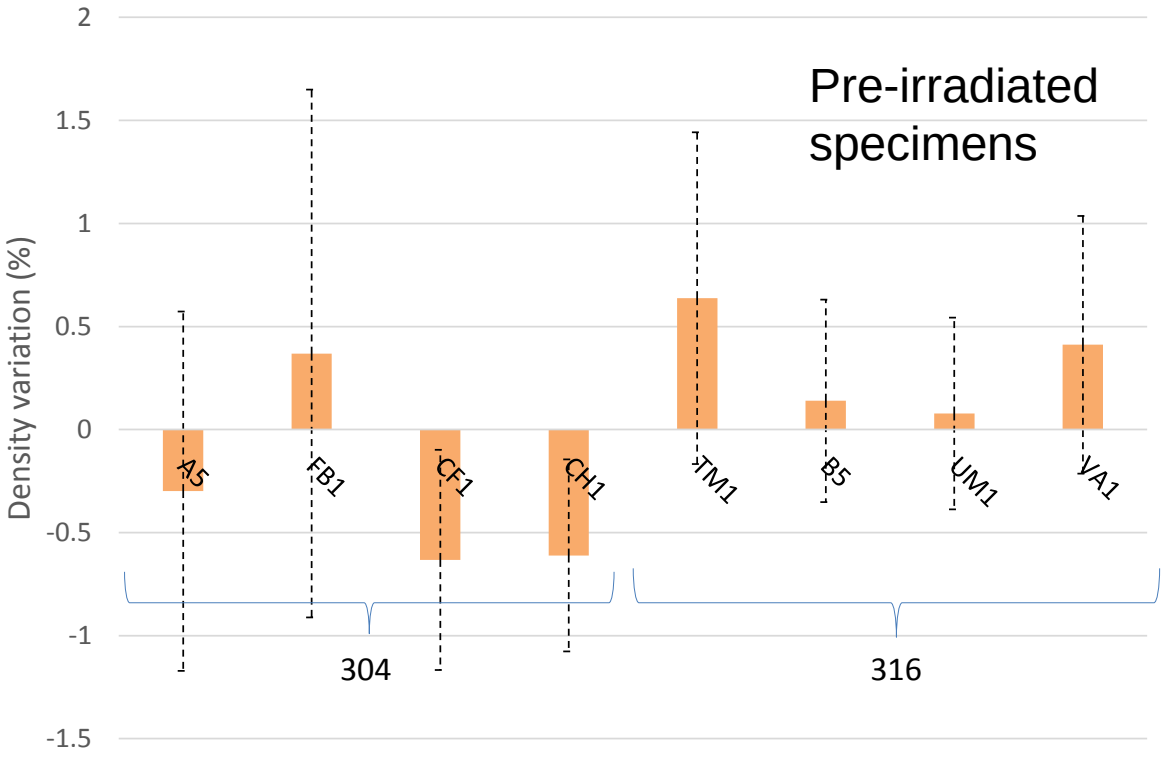
$t_{phases\ 1\text{-}4}$ = 12.71, $t_{phases\ 5\text{-}7}$ = 3.182, $t_{phase\ 8}$ = 2.776

- Overall confidence interval = Precision + Student-Law interval
- Confidence interval reduced for last phases
- Δd confidence interval = $(Precision + Student\text{-}Law)_{Pi} + (Precision + Student\text{-}Law)_{Pj}$

2.1. RESULTS – DENSITY MEASUREMENTS

- Evolution of density after GONDOLE irradiation program (comparison of density before GONDOLE irradiation and after the 8 phases of irradiation)

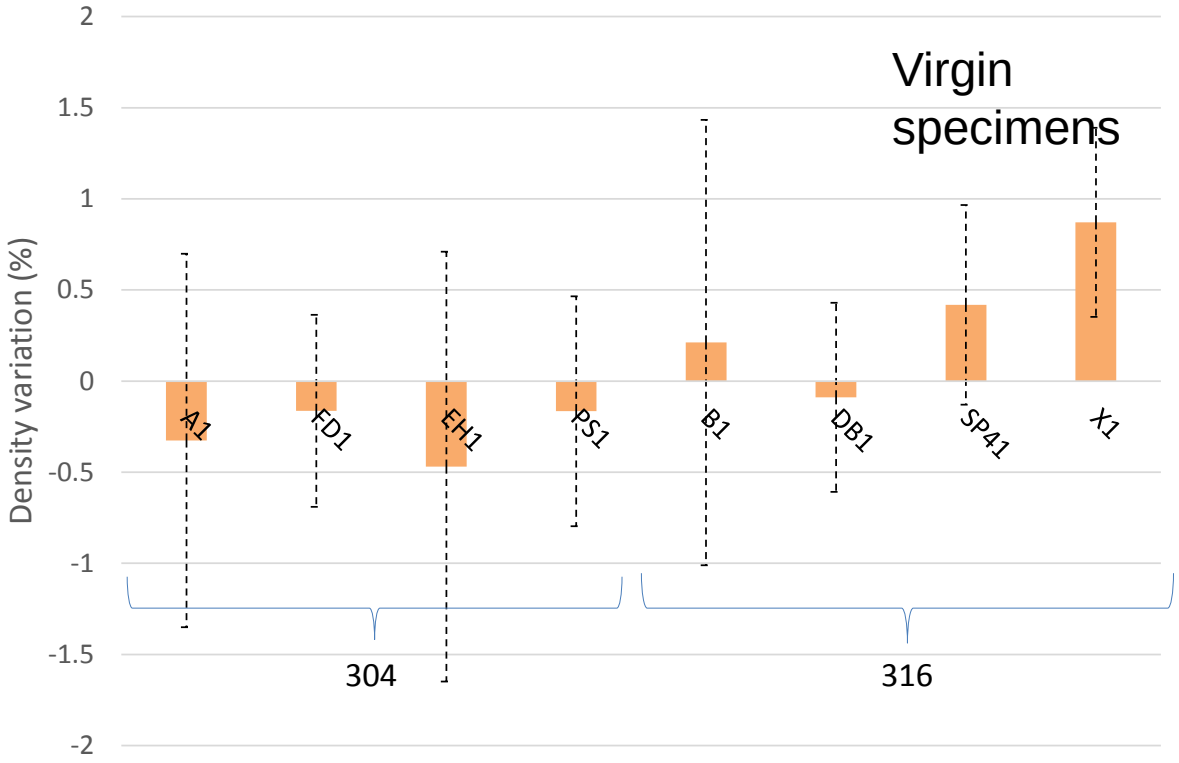
- Positive values = densification
- Negatives values = swelling



- Positive and negative variations

- Limited variations in the uncertainty range
- Small variations on CF1 and CH1

2.1. RESULTS – DENSITY MEASUREMENTS



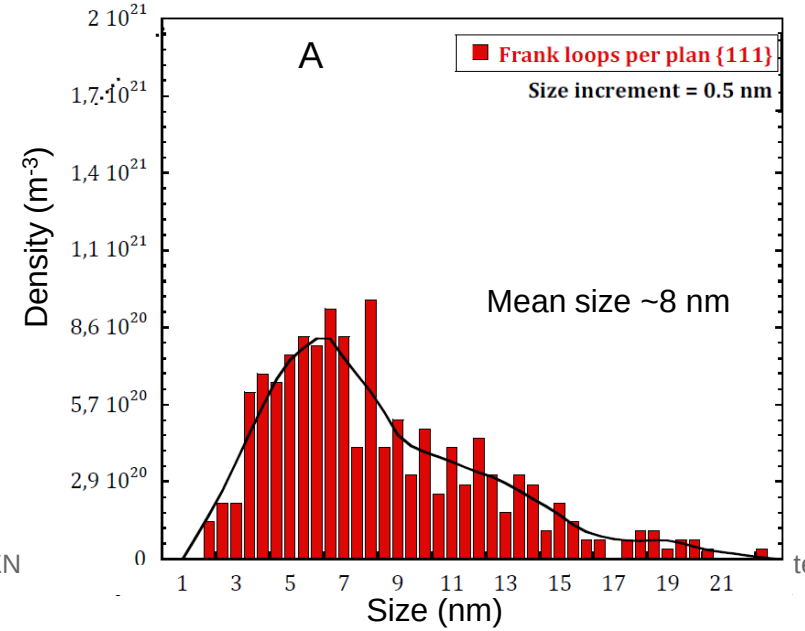
- ➢ Same results as pre-irradiated specimens
- Positive and negative variations
- Limited variations in the uncertainty range
- Small variations on X1

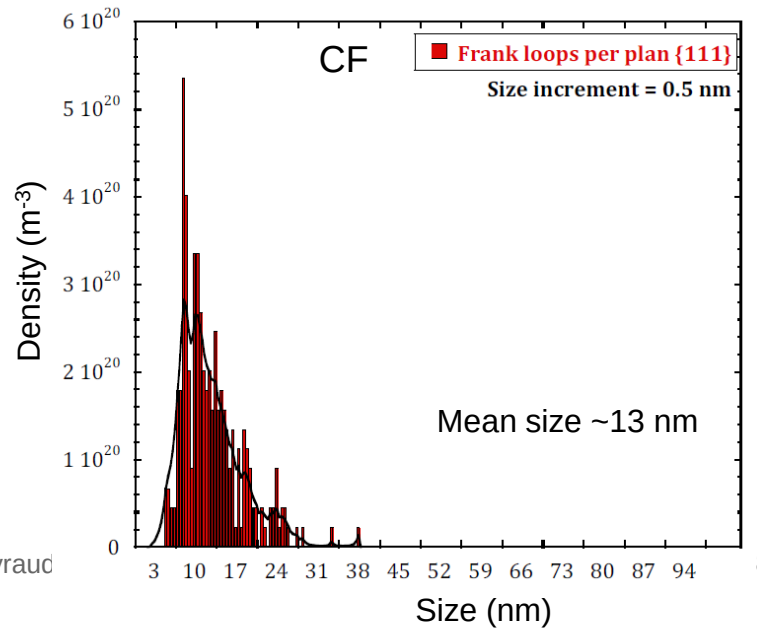
- Density measurements revealed that the density evolution are small and in the uncertainty range (virgin and pre-irradiated specimens)

2.2. RESULTS – TEM CHARACTERIZATIONS

- At stages 3 and 4, specimens were also introduced as TEM disks in tubes
- TEM disks removed after part 1 for TEM characterizations:
- A (pre-irradiated) specimen – 24 dpa – 375°C
- CF (pre-irradiated) specimen – 44 dpa – 375°C

- Irradiated microstructure (both materials):
- Frank loops
- Segments of perfect dislocations
- Precipitates
- Cavities





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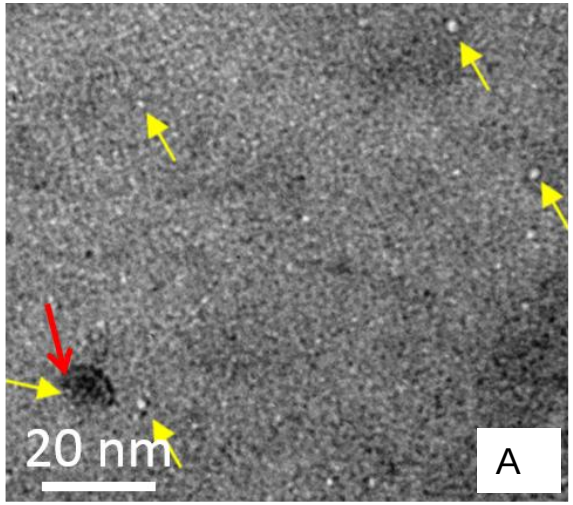
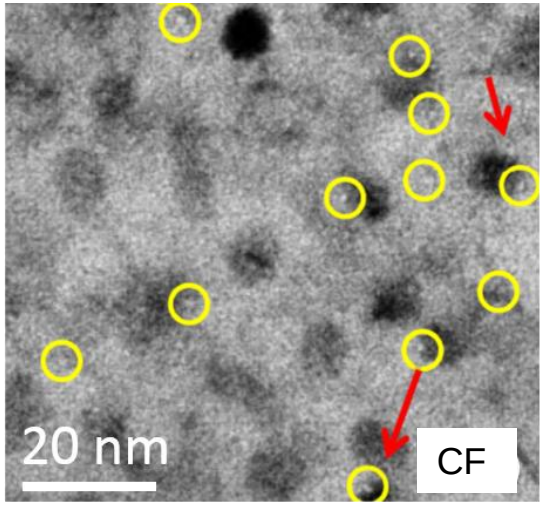
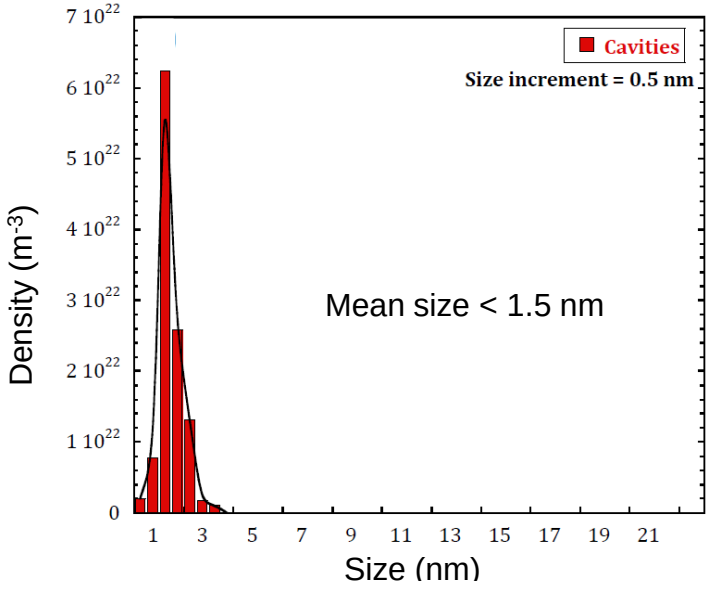
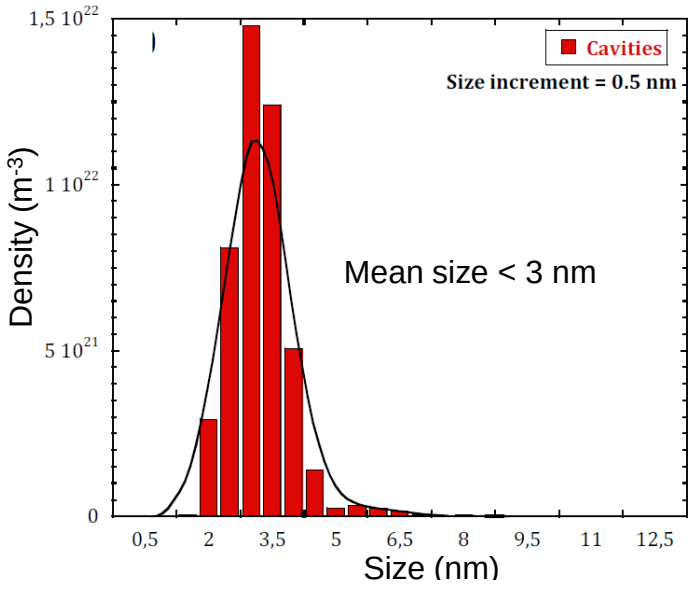
2.2. RESULTS – TEM CHARACTERIZATIONS

Cavities









- Small and numerous cavities
- Volume fraction limited (~0.04 and ~0.07%)

3. CONCLUSIONS AND PROSPECTS

CONCLUSIONS

- Description of the GONDOLE irradiation program
- Assessment of potential swelling by density measurements
- ➢ Description of the protocol and uncertainty measurements improvements
- ➢ Limited density variation, below the uncertainty limit
- ➢ TEM characterizations of pre-irradiated materials: cavities identification, limited associated swelling

Prospects

- To improve density measurements uncertainty (new measurements of the ‘before GONDOLE irradiation state’ - virgin specimens and some pre-irradiated archive specimens)
- To perform TEM characterizations of specimens available after phase 8

Thank you for your attention

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